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DEVELOPING AND USING EMPIRICAL MODELS FOR GEOTECHNICAL DESIGN IN UNDERGROUND COAL MINING

Mark Colwell[1]

ABSTRACT: This paper addresses several historical and contemporary issues that relate to the various modelling and analysis techniques utilised in the Australian underground coal industry to assist in geotechnical design and in particular ground support design, while focussing on the development and use of empirical techniques, which have substantially contributed to improving safety and productivity both in Australia and overseas.

In the field of mining geotechnics, the potential experience base is huge. For example many longwall panels are mined each year, and each one is a full-scale test of a pillar design and the ground support system(s) employed. The basic approach taken to develop empirical design tools utilising such information is described with examples including Analysis of Longwall Tailgate Serviceability (ALTS), Analysis and Design of Rib Support (ADRS) and Analysis and Design of Faceroad Roof Support (ADFRS).

This paper demonstrates that empirical techniques (based on a sound mechanistic understanding of the geotechnical environment) are particularly relevant and beneficial in dealing with the complexities of geotechnical design associated with underground coal mining resulting in far superior design tools as compared to that offered by numerical or purely analytical techniques.

INTRODUCTION AND BACKGROUND

This paper addresses several historical and contemporary issues that relate to the various modelling and analysis techniques utilised in the Australian underground coal industry to assist in geotechnical design and in particular ground support design.

Furthermore it is hoped that this paper can make a significant contribution (moving forward) that allows geotechnical practitioners to better understand that an empirical method based on a sound mechanistic understanding of the geotechnical environment can readily become a colliery's principal operational design tool in conjunction with the mine-site geotechnical engineer utilising their experience, training, site specific knowledge as well as simple common sense and other geotechnical tools if required.

There is a view held by a number of geotechnical practitioners (and regurgitated by others), which tends to pigeonhole the use of empirical techniques for "planning purposes" as opposed to being one's frontline ground support design tool, with others envisioning that empirical techniques will become unnecessary, e.g. Seedsman *et al* (2009) argue, "*that if the mechanics of the problem are understood, the simplicity of the coal mining geometry and modern stress analysis tools makes the empirical approach unnecessary.*" It is highly unlikely that this will ever occur or is in anyway desirable for effective ground support design, however developing an analytical model (even at the conceptual stage) to assist in understanding the mechanics of the problem is extremely important.

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Brady and Brown (2004) state, "*Whenever possible, it is desirable that mining rock mechanics problems be solved using the analytical tools and engineering mechanics-based approaches discussed in later chapters of this book*". The issue is however that it is not always possible and in fact with respect to underground coal mining is rarely, if ever, fully possible.

In addition even if the analytical model becomes a credible tool for ground support design purposes, then the end result of virtually all analytical models is a Factor of Safety (FOS) and to determine a suitable design FOS (and then to relate this value to a Probability of Failure), requires a database of information which can be statistically analysed if the model is to be applied across an entire industry without further site specific calibration.

In reality all geotechnical models utilised for design associated with underground coal mining are in fact empirical in nature as calibration is typically required and sound engineering judgement will always need to be used when applying any design outcomes. It does not matter whether the *engine room* of the model is analytical or numerical as either will require significant calibration prior to the model being effectively or confidently utilised for design purposes, whereas the calibration process is intrinsically a part of an empirical model whose *engine room* is an industry database.

It is acknowledged that empirical methods based on simple statistical analysis (e.g. simple linear regression forcing the regression line through the origin and/or "eyeballing" in upper and lower design boundaries) can be extremely limited in their application, particularly where it has not been demonstrated that the plotted parameters faithfully represent the mechanics of the problem. Geotechnical practitioners who have been exposed to these types of empirical methods may find it difficult to appreciate that empirical techniques, such as ALTS 2009 (Colwell and Frith, 2009), ADRS (Colwell, 2004) and ADFRS (Colwell and Frith, 2012), can actually be based on a sound mechanistic understanding of the geotechnical environment.

Galvin (2016) acknowledges that empirical methods, which are based on a clear understanding of the underlying physical phenomenon, assumptions made and the databases used for their development, can form the bases of valuable design tools. However, Galvin's (2016) overall commentary with respect to empirical methods is confused and somewhat disparaging particularly in relation to the various statistical techniques that can be used and how they are employed i.e. via the use of spreadsheet software. In addition, as no specific examples are given it is unclear as to who's work Galvin (2016) is attempting to disparage when using terminology such as "*oblivious*" and "*contrived*".

In the development of ALTS, ADRS and ADFRS design methodologies, effective use was made of statistical techniques ranging from mean and standard deviation, simple linear regression, multiple linear regression and logistic regression and in many instances, Microsoft Excel was utilised to undertake the analyses. The selection of the statistical technique to be employed is dependent on a clear understanding of the issues listed by Galvin (2016) as well as a clear understanding of the desired outcome.

Galvin (2016) in reviewing the empirical method states, "*Advances in numerical analysis are providing more reliable insight into the mechanistic relationships between parameters and their relative influence on ground behaviour, hence resulting in some applications of empirical analysis becoming obsolete*", while providing no practical examples of what empirical techniques have become "obsolete". Furthermore, as this paper demonstrates, numerical analysis does not provide a more reliable insight with respect ground/roadway behaviour associated with underground coal mining. Numerical modelling is primarily a stress analysis tool and its application to ground support design is a dubious extension of its application.

Unfortunately there are numerous examples of where geotechnical practitioners overstate the benefits of numerical modelling while virtually deriding the use of empirical techniques in terms of ground support design. In one such instance (as a result of ACARP Project C12011: Review of Barrier Pillar, Bleeder, Chain Pillars in Weak Strata and Thick Coal) in relation to roadway/tailgate strata failure, Fabjanczyk *et al* (2006) state that, "*The conditions required to initiate the failure mechanisms are site specific and make empirical techniques inappropriate"* and yet all four sites in that project (i.e. Moranbah North, North Goonyella, Southland/Austar and Angus Place) are a part of the ALTS database and where the tailgate performance was readily predicted by the ALTS Design Methodology at that time (i.e. ALTS II, refer Colwell, *et al,* 2003).

It would appear that rock mechanics scientists have a strong preference with respect to numerical modelling, however it is the author's contention that a good engineer will use all that science has to offer to model what is a complex environment to achieve realistic, cost effective and safe design outcomes that can be effectively utilised by a colliery (and if possible by an entire underground coal industry) as a part of their Strata Management Plan (SMP).

To repeat and reference all the misleading comments with respect to empirical techniques would take up much of the word allotment for this paper, however in the context of this paper it is worth reviewing one specific example in relation to rock mass classification systems, which are typically utilised by empirical techniques with respect to ground support design.

It is not uncommon to read in technical papers/publications (e.g. Calleja, 2008, Seedsman, 2008 and Galvin, 2016) a quote (or aspects thereof) taken from one of the editions of Brady and Brown (2004) with respect to rock mass classification systems which reads; *"Although the use of this approach is superficially attractive, it has a number of serious shortcomings and must be used only with extreme care. The classification scheme approach does not always fully evaluate important aspects of a problem, so that if blindly applied without any supporting analysis of the mechanics of the problem, it can lead to disastrous results."*

If one reads and accepts the above quote then it is highly likely that one would not be inclined to utilise rock mass classification systems or empirical techniques for ground support design, however directly following the above quote and within the same paragraph, Brady and Brown (2004) state, *"It is particularly important to recognise that the classification schemes give reliable results only for the rock masses and circumstances for which the guide-lines for their application were originally developed. It is for this reason that considerable success has been achieved in using the approach to interpolate experience within one mine or a group of closely related mines."*

The above quote puts an entirely different perspective on the issue and significantly changes the context, such that a geotechnical practitioner can now better appreciate the benefit of empirical techniques or at least take the time to investigate such a technique for their particular application. It is only reasonable that if the above Brady and Brown (2004) quotes are used, then they should be used in their entirety.

Other branches of science still embrace the empirical approach, for example the empirical method has resulted in many of the phenomenal accomplishments of modern medicine. There is still no satisfactory "numerical model" for the human body, yet new drugs are approved every day based on empirical studies and controlled trials. Medicine does not question the benefits or the continued need of this basic methodology; it simply understands the limitations and applies the results accordingly both in terms of research and medical treatment.

Why therefore would we as geotechnical engineers deny ourselves the use of the same successful scientific method? Furthermore there are three basic questions that an engineer should ask in applying a design technique; *"is the technique credible in terms of the application for which it is being used?"*, *"what are the practical benefits that the technique offers in terms of safety, productivity and cost-effectiveness?"* and lastly, *"what benefits, if any, would other methods provide, over and above the technique in question?"*

Therefore it is unfortunate but necessary that a paper such as this is published, so that the geotechnical community can better understand how empirical methods based on a sound mechanistic understanding of the geotechnical environment are developed and used as well as the significant benefit they offer the minesite geotechnical engineer.

MODELLING OF COAL MINE ROOF/RIB BEHAVIOUR

In relation to coal mine roof/rib behaviour and geotechnical evaluation/ground support design, there have been four basic approaches in relation to either modelling this environment or in the development of design tools which in alphabetical order are:

- Analytical
- Empirical
- Numerical
- Physical

An example of a Physical Model is illustrated in Figure 1, which is the same as Figure 126 taken from Hoek and Brown (1980) where they state, *"Figure 126 illustrates the buckling of slabs in the roof and floor of an excavation in a high horizontal stress field. This type of failure was observed in model studies conducted by the Australian Coal Industry Research Laboratory (ACIRL) in an attempt to simulate the structural and stress conditions in the coalfields near Sydney, Australia."*

Brady and Brown (2004) discuss the limitations of physical modelling, however they also state. *"The method is particularly appropriate where structural features exercise a dominant role in rock mass response"*. In terms of horizontally bedded roof, the major structural feature is the bedding along which delamination (i.e. tensile/shear failure) occurs resulting in thinner (or slender) beams, which can buckle under sufficient horizontal stress with ensuing shear failure of the rock as illustrated by Figure 2. Figure 3 illustrates similar behaviour associated with the ribs where delamination can occur along the cleat, coal joints as well as mining induced fractures.

The physical modelling studies conducted by ACIRL were extremely useful in better understanding the behaviour and failure mechanisms associated with underground coal mine roof and ribs and in conjunction with research undertaken since that time (particularly in reviewing extensometry information), it is clearly apparent that slender beam/column behaviour or buckling is the dominant behavioural/failure mechanism occurring within the immediate coal mine roof and rib which, if not controlled, leads to large scale roof/rib displacement and potentially a major collapse.

Figure 4 is a sonic probe extensometer plot displaying significant roof displacement, i.e. Total Roof Displacement (TRD) of approximately 90 mm and Height of Softening (HOS) to at least 4 m above the roofline. This particular plot clearly illustrates both how the roof delaminates into thinner beams and also how the 1.8 m bolts (that were utilised to reinforce this roof) modify the beam behaviour via the roof reinforcement mechanism of "beam building". The concept being that the bolts and cables create "thicker" beams within the reinforced section (or the primary bolted interval) and that a thicker beam will have a greater lateral load bearing capacity than a thinner beam.

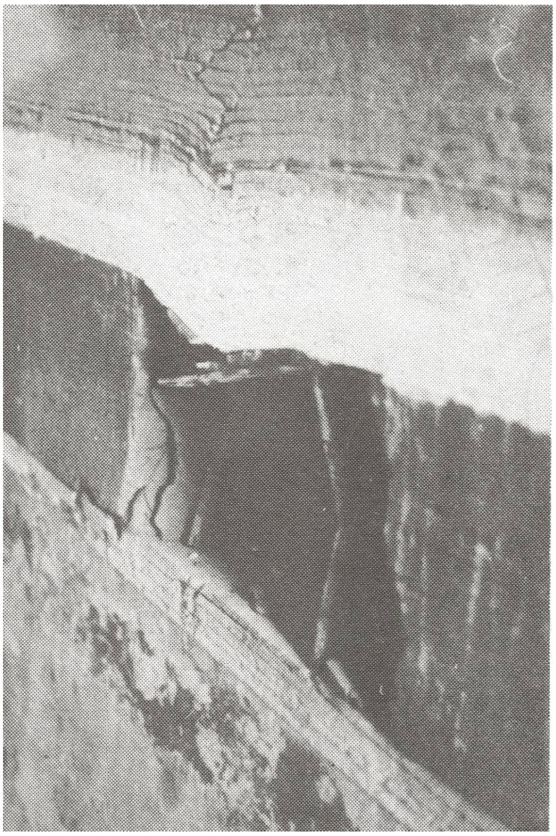

Figure 1: ACIRL coal mine roadway physical model (after Hoek and Brown, 1980)

Figure 2: Coal mine roadway roof displaying buckling and shear failure due to horizontal stress (after ARBS Help File, 2012)

Figure 3: Blockside ribline buckling – Appin colliery (after Colwell, 2004)

Figure 4 illustrates the behaviour (or response) of a section of maingate roof during and subsequent to longwall retreat. Under the action of horizontal stress, bedding and/or weakness planes can be forced apart and thinner discrete beds or beams of roof material start to form. This inevitably results in discernible roof displacements and roof softening (i.e. delamination) progressing higher into the roof as the magnitude of deformation (i.e. TRD) increases.

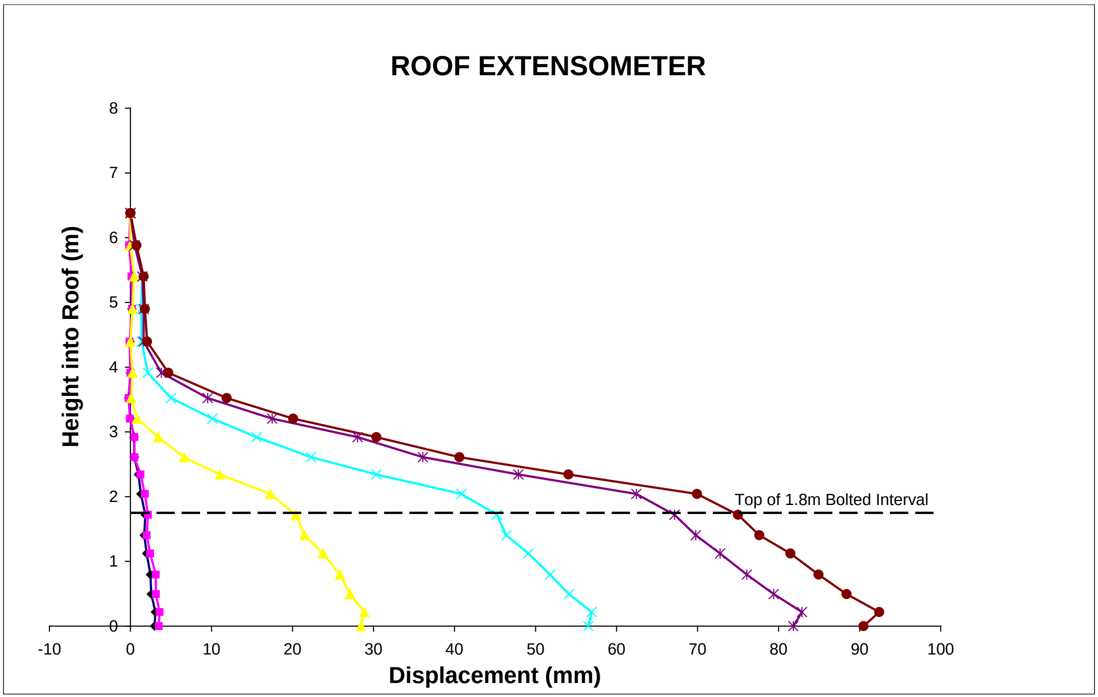

Figure 4: Roof behaviour adjacent to longwall extraction

The dashed horizontal line on Figure 4 represents the top of the 1.8 m primary bolted interval and there is an obvious difference in roof behaviour at this location within the roof. The response of the roof within the bolted interval is that of thicker beams as compared to the roof material overlying this interval (which is one of a series of thinner beams) up to the extent of the roof softening, which is approximately 4 m.

It is worth emphasising; that in stating that slender beam/column behaviour is the dominant behavioural/failure mechanism occurring within the immediate coal mine roof and rib, in no way should that be interpreted to mean it is the only failure mechanism. In terms of analytical modelling, Colwell and Frith (2010) utilise the mechanics of slender beam behaviour as the basis for the development of AMCMRR (Analytical Model for Coal Mine Roof Reinforcement), while accounting for the compressive failure of thicker beams which do not fail due to buckling.

It is worth noting that ALTS 2009 and AMCMRR were developed via the ALTS 2006 Project, which was conducted over a three year period while being funded directly by individual collieries and mining companies. Midway through the project, Emeritus Professor Ted Brown was commissioned to review the analytical model in its form at that time and concurred that, *"under the elevated horizontal stress conditions applying in many underground coal mines, particularly following longwall extraction, slender beam behaviour is, indeed, the dominant coal mine roof mechanism. It follows that this mechanism should be accounted for in any empirical, analytical or numerical approach to underground coal mine roof; and roof support design."* (Brown, 2007).

Brown (2007) provided further guidance and addressed some of the limitations of the analytical model, which were also recognised by the developers and where possible these were addressed prior to providing the final analytical model to the industry i.e. AMCMRR, with the major advancement, being the reasonable quantification of the beam building roof reinforcement mechanism.

The reinforcement mechanism or concept of beam building (as discussed by Mark, 2000) associated with the installation of roof bolts has long been recognised in the underground coal mining industry. While numerous researchers (e.g. Peng 1998, Gale *et al* 1992 and Seedsman *et al* 2009) have discussed the various mechanisms by which the bolts act to "create thicker beams" (i.e. by maintaining friction on bedding planes etc.), AMCMRR was the first geotechnical design tool that in a practical way attempted to quantify the beam building effect.

Like all geotechnical models AMCMRR has limitations, however it provides a reasonable analytical solution to a complex issue while realistically incorporating the reinforcement mechanisms associated with slender beam behaviour i.e. beam building and mechanical advantage. Furthermore it was always the intent that AMCMRR should initially be used and calibrated on a site by site basis (in terms of a suitable design FOS). This in fact is typical of how many (if not most) analytical and numerical models are utilised by experienced geotechnical engineers.

In addition, AMCMRR was developed to be used in conjunction with the ALTS Design Methodology as it is the ALTS Design Methodology that has been formulated to complement the Australian minesite risk management approach to strata control/management and this aspect will be discussed later in the paper.

The original ALTS Design methodology (Colwell, 1998) and ALTS II (Colwell *et al*, 2003) specifically dealt with tailgate design for the vast bulk of tailgates/chain pillars subject to double pass longwall extraction with the focus being the tailgate intersection performance with the retreating longwall face (i.e. refer Position d, Figure 5) as the design condition.

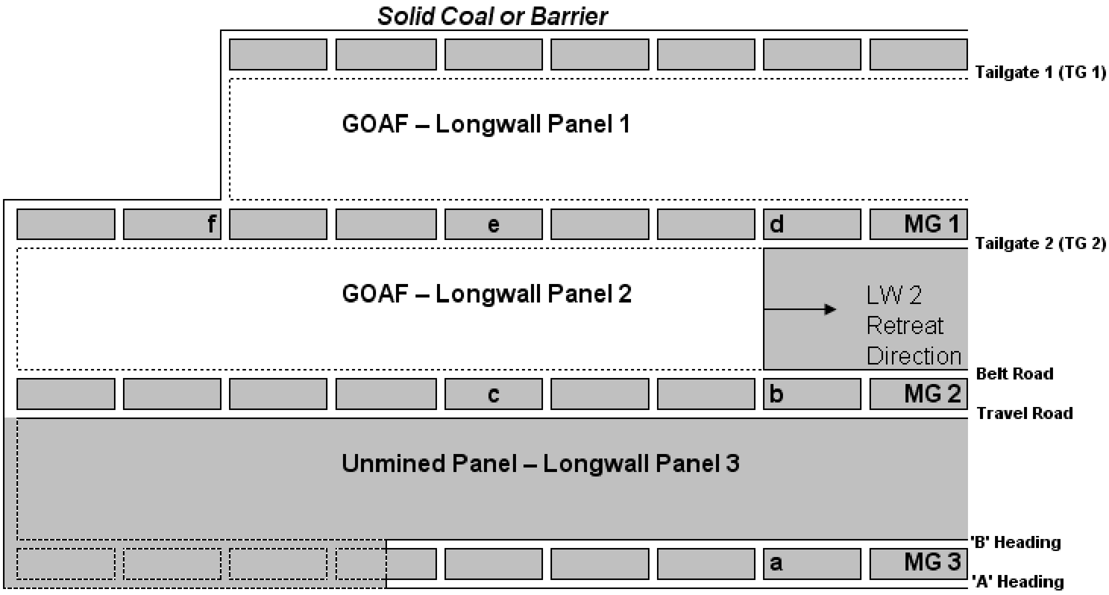

Figure 5: Typical Australian longwall layout

As a result of the ALTS 2006 Project, ALTS 2009 now contains roof support design modules for Maingate Belt (MGB) Road roof support design as well tailgates subject to *Single and Super Stress Notch* conditions and in addition the ADRS module for rib support assessment and design.

The interested reader is referred to Colwell and Frith (2009) and Colwell (2010a) for a more detailed description of ALTS 2009, however for the purposes of this paper the development of the MGB Roof Support Design Module within ALTS 2009 will be used to illustrate the process by which an empirical model is developed and will be discussed in the subsequent section of this paper.

With the advent of more powerful computers in the late 80's early 90's, a significant number of researchers in the field of rock mechanics moved away from empirical, analytical and physical models to numerical modelling. While the modelling of rock behaviour using numerical methods has improved and mathematical routines have been developed in an attempt to account for both elastic and plastic behaviour (e.g. FLAC – Gadde and Peng, 2005, Gale and Tarrant, 1997 and Gale *et al*, 2004; 3STRESS – Medhurst, 1996 and MAP3D – Palmer and Morrison, 2005), the various models do not incorporate mathematical routines associated with buckling.

In addition these researchers have been considering geometries (or setting up their models) which contain structural elements that, by their very nature, cannot buckle and must fail in either direct compression (as one would observe in a laboratory based strength test) or shear. This is in complete contrast to the slender beams associated with coal mine strata, which either form the immediate roof or quickly develop within the immediate roof due to roadway formation or as a result of a horizontal stress increase.

Therefore it is not surprising that the issue of buckling as a failure mechanism about coal mine openings/roadways has been largely ignored by researchers that rely heavily on numerical modelling in an attempt to replicate and understand roadway behaviour. However Gale (2018) takes this to a whole new level; while accepting that it is common to see coal ribs, which are *"apparently"* buckled (e.g. refer Figure 3), for Gale (2018), somehow this is caused by conjugate shear failure behind the buckled zone. Gale (2018) applies this same theoretical numerical modelling to the roof as well and illustrates how erroneous conclusions can be reached where the necessary mathematical equations/code are missing.

One of the primary reasons that numerical models (as they are being used with respect to the Australian underground coal industry) require a high level of calibration via parameter manipulation is that the modelling process does not include the mechanistic principles of the dominant behavioural/failure mechanism occurring within the roof/ribs. The geotechnical environment, rock mass failure modes and the way in which roof and rib support interacts with the rock mass are complex issues and therefore it is generally recognised that without prudent simplification, the complexity of the problem will overwhelm all current geotechnical methods of modelling, however to simply ignore and now apparently dismiss the dominant behavioural/failure mechanism occurring within the roof/ribs means the model has little credibility in terms of actual ground support design.

Tarrant (2005) suggests that researchers utilise numerical modelling, to develop a "better understanding" of roadway behaviour. Tarrant (2005) points out that, *"Use of such tools is limited by the simplifications required however when used in conjunction with field measurement and observation, the model findings can be tested and a level of confidence in the results defined."*

The use of numerical modelling in the manner described by Tarrant (2005) generally only provides a calibrated (via measurement) model to then be used for site specific prediction or design. Calibrating a numerical model to a limited number of sites does not provide an underground coal industry with a widely applicable and therefore accepted design tool for roadway ground support design. This is particularly the case when the numerical model being calibrated to said roadway behaviour does not incorporate mathematical code associated with buckling. Invariably one finds that in these instances the researcher does not produce a model or design technique that can be readily utilised by industry and typically the numerical model remains within the domain of the researcher for its application.

A perfect example of the above is ACARP Project C12006 entitled, "Standing Support – It's Time for an Engineered Solution" (Tarrant, 2005). This project was funded on the premise that, *"There are currently no methods that provide mine operators with reliable tailgate support design"*, (refer ACARP 2002 Project Selection Newsletter). This statement being made even though 1) ALTS was one of only 11 ACARP geomechanics-related projects which received the highest possible rating (in terms of research quality and industry application) based on a review of 52 underground geomechanics-related projects by Emeritus Professor Ted Brown (refer Brown, 2001) and 2) ALTS II (Colwell, *et al*, 2003) had been available to and utilised by the industry for some two years at that point and was the subject of the information provided in 2001 to ACARP Project C9108 (i.e. Gale and Hebblewhite, 2005).

The final report associated with ACARP Project C12006 contained Section 4 entitled, "Tailgate Support Design Methodology", which was all of one page in length such that if a colliery actually wanted to use this "methodology" then it would be quite difficult without utilising the services of SCT Operations Pty Ltd. This contrasts to the author's final ACARP reports in relation to ALTS (Colwell, 1998), ADRS (Colwell, 2004) and ADFRS (Colwell and Frith, 2012) where the design methodology is fully detailed such that an engineer could programme their own design software if they wanted to.

DEVELOPING AN EMPIRICAL MODEL FOR MAINGATE BELT ROAD ROOF SUPPORT DESIGN

In developing an empirical model, the initial approach is to clearly identify what is the desired outcome and then to assess (via a literature review and using one's own experience) what are the important factors affecting (or significant predictors of) that outcome and most importantly is that the initial concept and the eventual geotechnical design technique developed is consistent with Newtons Laws, which govern the physical world associated with an underground coal mine.

In terms of an Australian longwall mine's belt road, the desired outcome is to quantify the level and type of roof support (as well as timing of installation) required to maintain satisfactory roadway conditions during and subsequent to development (i.e. Position a – 'B' Heading, refer Figure 5) and up to the maingate belt intersection with the retreating longwall face (i.e. Position b, refer Figure 5).

In terms of any coal mine roadway, it is necessary to take into consideration that it is not just a roof fall that would be considered an unsatisfactory outcome as practical mining considerations require that the roof be maintained with a satisfactory level of stability during longwall retreat so as to minimise any potential negative impact on longwall production, knowing that productivity and safety can be adversely affected by simply excessive roof convergence trapping equipment (e.g. stage loader) or deteriorating roof conditions necessitating the installation of remedial roof support.

It also needs to be recognised that with respect to belt roads the installation of remedial support about the belt is difficult, will inevitably cause production stoppages and is essentially unacceptable, unlike a tailgate where a low or moderate level of remedial support in isolated areas (while of course never desirable) would be likely to have a lesser impact on safety and/or productivity. Therefore a more conservative approach to belt road roof support design (as compared to a tailgate where there is also the option of standing support) is understandable and generally warranted.

However, once again in terms of practical mining considerations, it is important to appreciate that an overly conservative roof support design may result in the belt road roof "hanging up" in the goaf inbye of the longwall supports causing ventilation problems. Ground support design associated with coal mine roadways is far different from a civil construction associated with tunnelling and has unique challenges.

The next part in the development of the model is to start with a simple model or concept, to which one can subsequently add the layers of complexity if or as required. In this instance (and with experience) the assessment was made that the level of support required to maintain satisfactory roadway conditions throughout the mining cycle, would primarily be a function of 1) some measure or index that relates to the structural integrity/lateral strength of the immediate roof and 2) the horizontal stress acting across the roof as a result of roadway formation then subsequently the belt road horizontal stress concentration effect associated with longwall retreat.

The above determination allows the researcher to collect the necessary minesite information for inclusion in the database, for example:

- All information that relates to the tendon support (i.e. bolts and longer cables) installed off the continuous miner during development as well as any additional support installed prior to longwall retreat with this including (but not limited to) the Mine Manager's Support Rules, secondary support plans, roof support hardware specifications, Trigger Action Response Plan (TARP) and Strata Management Plan (SMP).

- All related borehole information e.g. geological/geotechnical logging and geomechanical (laboratory and field) testing of borehole core, underground mapping information with respect to structural discontinuities associated with the roof and the use of an appropriate rock mass classification system that can readily utilise this information.
- All available and relevant in situ stress measurement information and the mine layout/geometry (such as longwall retreat direction and depth of cover contour plan) so that the resultant horizontal stress acting perpendicular to roadway development (i.e. σ_{R}-Dev, MPa) and subsequently the stress acting across the roof of the belt road adjacent to the intersection with the longwall face during retreat extraction (i.e. σ_{R}-MGB, MPa), can be assessed.

In relation to points 1 and 2 and with respect to previous ALTS research, there had been considerable success in using the roof support ratings PRSUP and GRSUP and the Coal Mine Roof Rating (CMRR) rock mass classification index, so naturally it was decided that these indices would be utilised/assessed initially.

The Primary Roof Support (PRSUP) Rating is a measure of the bolting capacity (kN) per square metre of roof normalised to the primary bolted interval and includes all bolt/tendon support that is installed off the continuous miner or mobile bolter as part of development, whereas the Ground Support (GRSUP) Rating incorporates all bolt and longer tendon roof support installed within the roof of a roadway into a single rating, regardless of when the roof support is installed. This includes all roof bolts, longer tendons, cables and trusses.

The GRSUP is calculated in a similar manner to that of the PRSUP; in fact if no additional support is installed within the roof subsequent to that installed off the continuous miner or mobile bolter then GRSUP will equal PRSUP. The interested reader is referred to Colwell and Frith (2009) where the calculation of these roof support ratings is fully detailed.

The CMRR was calculated using both underground and borehole information as outlined by Colwell (2010b) which is fundamentally based on the information provided by Mark and Molinda (2003). The CMRR has now proven itself extensively in both the Australian and United States underground coal industries to be reliable indicator of the structural competence of the bolted mine roof interval. The primary reasons being, 1) the CMRR incorporates an index that directly relates to how a rock/coal unit will delaminate under horizontal stress and the resultant average beam thickness and 2) realistically weights the impact of beam thickness and UCS in terms of the structural integrity of the roof. The statement by Galvin (2016) that, *"the CMRR does not take account of behaviour mechanisms"* is simply incorrect.

The resultant horizontal stress acting perpendicular to the direction of drivage (i.e. σ_{R-Dev}) is calculated using equation 1 (refer Page 92, Hoek and Brown, 1980) which is derived from Mohr's Circles:

$$\sigma_{\mathrm{R}}\text{-Dev} = [0.5 \times (\sigma_{\mathrm{H}} + \sigma_{\mathrm{h}}) - 0.5 \times (\sigma_{\mathrm{H}} - \sigma_{\mathrm{h}}) \times \cos(2\beta)] \quad (1)$$

where:

σ_{H} is the magnitude of the major horizontal stress (MPa);
σ_{h} is the magnitude of the minor horizontal stress (MPa);
β is the angle between the roadway direction and the orientation of the major horizontal stress (refer Figure 6).

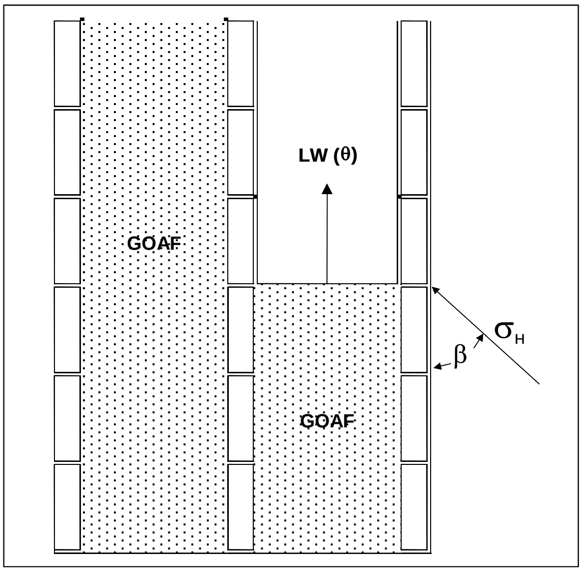

Figure 6: The angle β used to determine the values of σ_{R-Dev} and $\sigma_{R-\mathrm{MGB}}$

It should be noted that σ_{R}-Dev and σ_{R}-MGB are calculated and specifically relate to the primary bolted interval and therefore the Young's Modulus (*E*, GPa) and Poisson's Ratio (ν) of the coal/rock units associated with bolted interval are required as the *in situ* stress measurements are typically conducted in roof units above the bolted interval or below the coal seam.

The change and increase in horizontal stress in the roof that occurs about the belt road intersection with the longwall face during retreat extraction (i.e. refer Position b – Figure 5) is often referred to as *Maingate Stress Notching*. The magnitude of the resultant stress (in MPa) is denoted as σ_{R}-MGB and use was made of the research findings of Gale and Matthews (1992), Mark *et al* (1998) and Su and Hasenfus (1995) to estimate σ_{R}-MGB.

Gale and Matthews (1992) discuss the horizontal stress monitoring undertaken as a part of their study and the methods used so as to link a Stress Concentration Factor (SCF) to the angle between the longwall retreat direction and the major horizontal stress direction (i.e. the angle "β" - refer Figure 6). It is worth noting that Gale and Matthews (1992) detailed certain limitations associated with the methods used, however it is assessed that what was provided (i.e. the SCF relationship to β) is a reasonable approximation to a complex issue so that in conjunction with the Mark *et al* (1998) and Su and Hasenfus (1995) information, Colwell and Frith (2009) were able to analytically develop a process by which a reasonable estimate for σ_{R}-MGB can be made and the interested reader is referred to Colwell and Frith (2009) where its calculation is fully detailed.

Therefore it is recognised that σ_{R}-MGB is an approximation and not an "exact" calculation and therefore while its units are MPa (as used within AMCMRR), within an empirical model σ_{R}-MGB is an index that is utilised to "capture an effect", which in this instance is the stress notching effect about the belt road intersection with the retreating longwall face. Ultimately it is the strength of the various statistical relationships that will determine the quality of these indices.

The type of statistical technique which is used to analyse a database will primarily depend on whether the outcome (referred to as the dependent variable) is continuous or categorical. Many interesting dependent variables/outcomes are categorical e.g. patients may live or die, people may pass or fail exams, coal rib lines may collapse or be stable, roadway roof performance is satisfactory or unsatisfactory and so on. A range of statistical techniques have been developed for analysing data with categorical dependent variables, including discriminant analysis, probit analysis, log-linear regression and logistic regression.

The statistical technique of logistic regression was used in the development of ALTS, ADRS and ADFRS when analysing the various databases in terms of criteria based categorical outcomes, where the outcome is typically classified as satisfactory, manageable (being an appropriate category as all Australian coal mines employ a TARP and SMP) and unsatisfactory.

Logistic regression allows for the classification of cases or observations into two (or more) populations based on an outcome. Logistic regression is also able to distinguish which parameters (referred to as the independent variables) are significant predictors of a particular outcome and to then rank and quantify the relative importance of these independent variables on the outcome.

However in developing an empirical method for maingate belt road roof support design, it was decided that the desired outcome is to quantify the level of support to maintain satisfactory roof conditions subsequent to development and during adjacent longwall extraction via the roof support indices PRSUP and GRSUP (and therefore a continuous outcome), with the CMRR, σ_R-Dev and σ_R-MGB as the significant predictors of that outcome. In this instance the most appropriate statistical technique to use is multiple linear regressions.

The primary roof support database (developed via the various ALTS research projects) is drawn from both the travel road/tailgate and maingate belt road databases and comprises 109 Cases (representing 38 Collieries; being 36 longwall and two bord and pillar). Figure 7 presents the relationship for PRSUP along "Headings" plotted against the CMRR minus the Strong Bed Adjustment (i.e. CMRR - SBADJ).

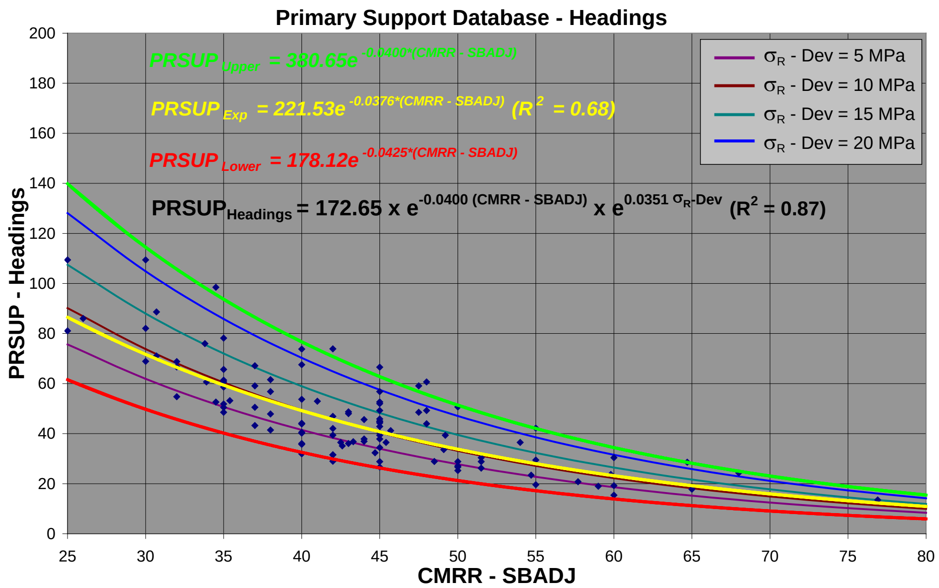

Figure 7: PRSUP v's (CMRR - SBADJ and σ_R-Dev) - Headings

It should be noted that "Headings" refers to that section of the belt road, travel road or tailgate (refer Figure 5) between cut-through intersections, while "Intersections" refers to those sections of the gateroad that intersect with the cut-throughs.

It was found during the course of the ALTS research that most collieries (as a part of their Support Rules) increase roof support levels within the intersections and for certain distances either side of the cut-through edge along the heading (i.e. inbye and outbye of the intersections).

This practice is consistent with the both the geotechnical environment and operational factors (as discussed by Colwell and Frith, 2009). Due to space constraints associated with a conference paper it is only the Headings analyses that are presented.

One of the most important concepts incorporated into the CMRR is that of the Strong Bed Adjustment (SBADJ). Many years of experience with roof bolting (in Australia and overseas) has found that the overall structural competence of mine roof is very often determined by the quality of the most competent bed (i.e. rock unit) within the bolted interval.

There are relatively few collieries in Australia (i.e. approximately 10% to 15% of the database) where the SBADJ is a significant issue or component of the CMRR, however it is apparent from the analyses (and field investigations) that at those collieries where the SBADJ is a significant component of the CMRR, if for *any* reason anchorage within the strong bed is compromised (i.e. due to gloving, water, installation difficulties) or the strong bed is absent within the bolted interval (for example due to a thickening of weaker strata beneath the strong bed or the strong bed "lenses out") then roof performance can be significantly and adversely effected particularly during longwall retreat.

If the reinforcing benefits associated with anchoring the bolts in a strong bed are lost then the primary roof support level (i.e. PRSUP) becomes even more critical in maintaining sufficient lateral load bearing capacity within the immediate roof. In such cases prudent engineering judgement dictates that the recommended level of primary roof support (as a part of the overall design process) is assessed in terms of the CMRR less the SBADJ.

The exponential trendline as well as the upper and lower boundaries (which statistically represent a 95% confidence level/interval) are displayed on Figure 7. Utilising the exponential trendline, the strength of the correlation (R^2) between PRSUP and CMRR - SBADJ for Headings is a relatively high 0.68. However with the inclusion of σ_R-Dev the correlation increases significantly and is an exceptionally high 0.87.

Figure 7 clearly illustrates that the PRSUP v's (CMRR - SBADJ) relationships for varying stress levels acting across the roof (i.e. σ_R-Dev) fit seamlessly within the upper and lower boundaries. The maximum σ_R-Dev associated with the primary roof support database is approximately 22.5 MPa.

The maingate belt road database comprises 58 satisfactory cases representing 33 longwall operations where the CMRR ranges from 25 to approximately 80 and the cover depth ranges from 100m to 510m. As previously discussed, the installation of remedial support about the belt is essentially unacceptable and therefore only those cases with a satisfactory outcome were utilised i.e. there were no production delays or safety concerns attributable to roof instability and certainly no roof falls or remedial roof support measures required.

Figure 8 plots GRSUP against the CMRR and σ_R-MGB and while a strong relationship exists between simply GRSUP and CMRR (i.e. $R^2 = 0.73$), with the inclusion of σ_R-MGB the correlation increases significantly and is an extraordinarily high 0.89. Once again the GRSUP v's CMRR relationships for varying stress levels acting across the roof (i.e. σ_R-MGB) fit seamlessly within the upper and lower boundaries. The maximum σ_R-MGB associated with the maingate belt road database is approximately 45 MPa.

In many ways there is a great deal of similarity between the basic engineering Factor of Safety equation (i.e. FOS = Load Bearing Capacity of a Structure/Applied Load) and the GRSUP/CMRR/σ_R-MGB relationship displayed on Figure 8. In terms of a belt road roof adjacent to the intersection with a longwall face, clearly σ_R-MGB is analogous to the *Applied Load*. If we replace the term *Load Bearing Capacity of a Structure* with *Load Bearing Capacity of a*

Reinforced Structure, then GRSUP and CMRR essentially “become” the *Reinforced Roof Structure* (as determined within AMCMRR). The difference between the two equations comes down to the outcome.

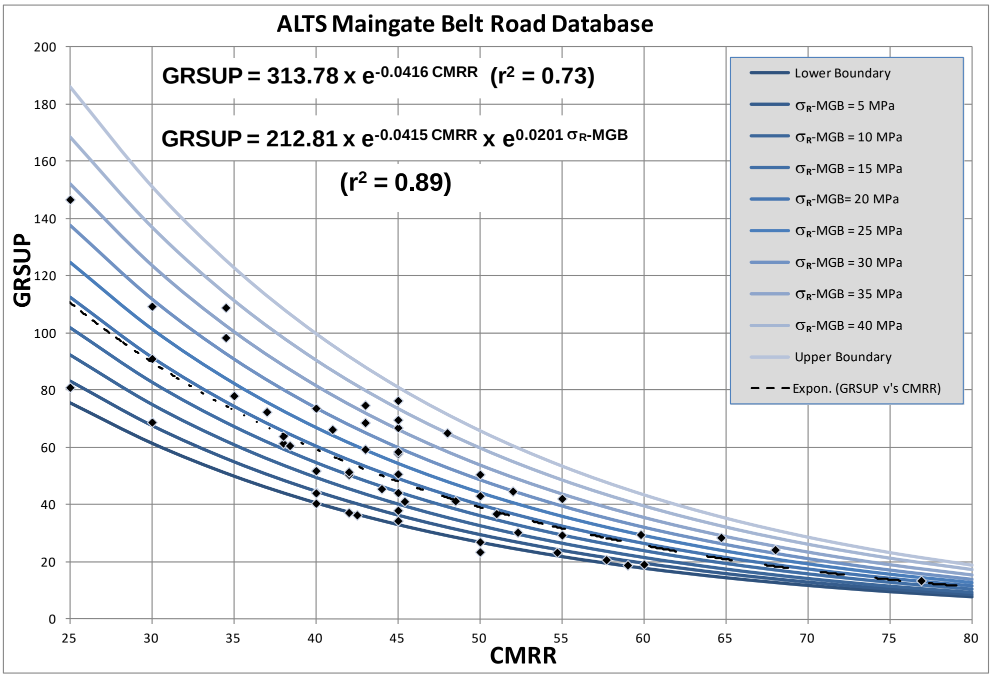

Figure 8: GRSUP v’s (CMRR and σ_R-MGB) – Headings

Prior to finalising the design methodology for maingate belt road design it is important to recognise that in addition to the geotechnical/risk related issues, operational factors directly influence the level of primary roof support utilised within the gateroads of Australian collieries. For example many collieries elect to install a level of primary roof support off the continuous miner greater than would be required to simply maintain satisfactory roadway conditions during and subsequent to development while prior to longwall retreat, as it may be operationally more convenient or effective to do so off the miner rather than installing secondary support at a later stage to maintain satisfactory roadway conditions during longwall retreat.

To assist in ascertaining this base level of primary roof support (designated as $PRSUP_{Dev}$) Colwell and Frith (2009) combined the maingate belt road database with a portion of the primary roof support database where it was assessed that the level of roof support installed off the miner was simply to maintain satisfactory roadway conditions associated with development and prior to longwall retreat. Therefore via this combined database the operational issue related to installing a level of roof support greater than that required to effectively deal with the resultant horizontal stress acting across the roof (i.e. σ_R-Dev or σ_R-MGB as the case may be) is substantially eliminated from the analyses.

This combined database of 90 cases for Headings presented in Figures 9 essentially represents a level of *reinforced* roof stability in terms of:

- A tolerable level of risk specific to Australian collieries and
- The two principal geotechnical drivers being the structural integrity of the immediate roof (as measured by the CMRR) and the resultant stress (σ_R).

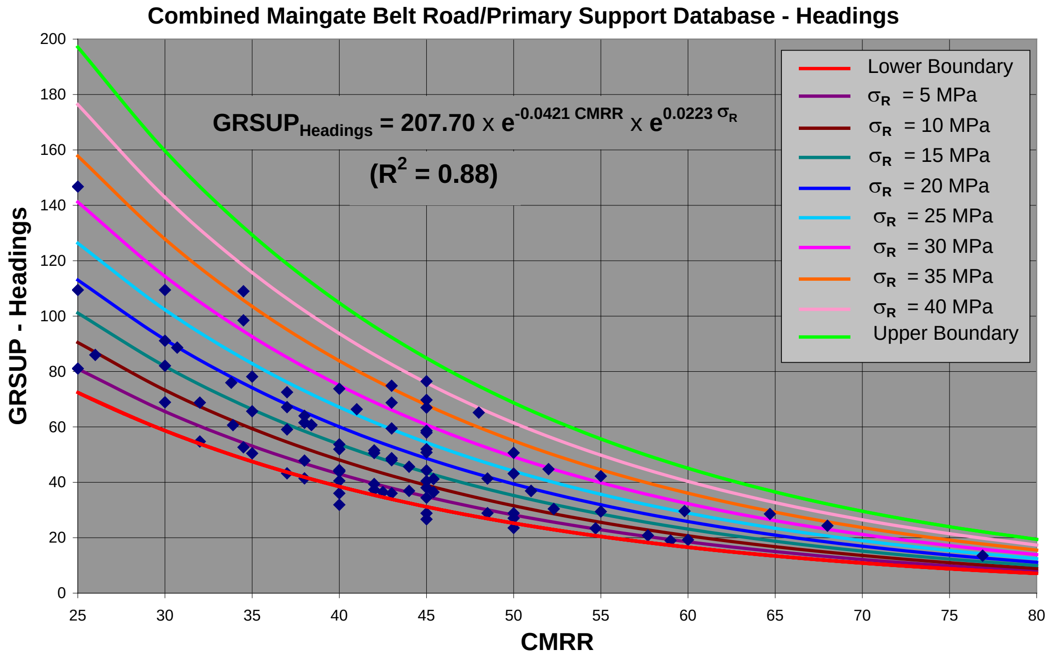

Figure 9: GRSUP v's (CMRR and σ_R) – Combined database – Headings

Based on the preceding information, the extraordinary strength of the various relationships associated with Figures 7, 8 and 9 (i.e. R^2 values ≈ 0.9) and previous experience, a maingate belt road roof support design methodology could readily be developed for Australian longwall operations, which provided options with respect to the timing of installation as well as the required level of support at the various stages of the development/longwall extraction cycle.

In developing the ALTS technique and database, information was collected over a 12 year period (i.e. early 1997 to end 2008) representing 36 longwall operations. During the course of the various ALTS and ADRS projects approximately 120 underground inspections were conducted to assist in the formulation of the database. During each site visit, information was collected via the underground inspections and discussions with colliery personnel. Subsequent to an underground inspection, a site inspection report was prepared which was then forwarded to the respective colliery for review and confirmation. This process was undertaken to ensure the integrity of the information contained in the database.

Furthermore contained in the ALTS 2009 software package for longwall gateroad design (which is utilised by approximately 70% of Australian longwall operations) are several resource documents (under the Help Menu) two of which are entitled, *"ALTS Summary"* and *"Computational Aspects of ALTS"*. Within these documents the process by which the recommended, upper and lower values (for each of the various design parameters) are determined and utilised is clearly outlined and design examples are provided to demonstrate the use of the equations and design methodology so as to fully detail the *inner working*s of the software, which is rarely if ever provided by the numerical modeller.

DEVELOPING ROOF SUPPORT PATTERNS UTILISING ALTS 2009

In utilising ALTS 2009 and the roof support indices PRSUP and GRSUP to develop roof support patterns there are three basic issues to be aware of:

- The various design methodologies within ALTS 2009 specifically relate to roof/rib support practices utilised within the Australian underground coal industry both in terms of risk and the hardware/installation practices employed.

- Typically a minesite geotechnical engineer will be starting with some established ground support practices at the mine and where there are changing conditions in terms of the geotechnical environment (e.g. CMRR, geological discontinuities encountered by the continuous miner affecting the CMRR and changes in the *in situ* stress) initially it is a quantitative measure of the necessary support densities, which are required. While at the feasibility stage it is essentially all about evaluating a quantitative measure of the required support densities, which PRSUP and GRSUP provide.
- ALTS 2009 (design methodologies and software) was formulated to be used by a suitably qualified geotechnical engineer (e.g. RPEQ Geotechnical Mining) with a reasonable level of underground coal mining experience.

BOLT AND CABLE LENGTH SELECTION

ALTS 2009 limits the bolt length selection from 1.5 m to 2.7 m, which is the extent of the database. However with respect to point 1 it is important to note that 62 of 109 primary roof support database cases utilise a 2.1 m length bolt while 34 employ a 1.8 m bolt length where the average is 2.0 m. Therefore the Australian underground coal operations predominantly utilise 2.1 m and 1.8 m bolt lengths and this is a reasonable starting point while then taking into account other issues that would impact on the final roof bolt length selection.

Furthermore ALTS and the subsequent ADFRS research demonstrated that for fully encapsulated bolts (as typically installed in Australia and accepting a certain level of variability in the quality of installation between pits and operators), the significant predictors of the bolts' effectiveness in terms of roof reinforcement are individually 1) the length of the bolts, 2) the capacity of the bolts (i.e. Typical Ultimate Tensile Strength, kN) and 3) the bolting density as well as when these are combined into the overall PRSUP Rating. The research of Mark *et al* (2001) reached the same conclusions.

A clear example of an underground coal industry (at that time) demonstrating that bolt length and bolting density has a significant impact on roof stability and the research approach taken, is that associated with the roof support design methodology developed by the CDC - The National Institute for Occupational Safety and Health (NIOSH) for the United States underground coal industry, ARBS (Analysis of Roof Bolt Systems – Mark *et al*, 2001).

Mark *et al* (2001) explain that with respect to their research, the "starting point" was an industry that had more than 1,500 roof falls occur each year in U.S. coal mines where the average bolt length was approximately 5 ft (≈ 1.5 m which is the Australian lower limit), four bolts per row had become the near universal standard and bolt spacing was limited by law to 5 ft, but was seldom less than 4 ft. In analysing their database the outcome variable, which measured the success of the roof support system, was the number of Mine Safety and Health Administration (MSHA) reportable roof falls that occurred per 10,000 ft (3,048 m) of drivage, which were solely related to roof falls during or within 18 months of development and excluded any falls associated with longwall retreat.

In analysing their database Mark *et al* (2001) utilised a form of discriminant analysis based on the following three categories:

- *Failures* (more than 1.5 roof falls per 10,000 ft of drivage)
- *Intermediate* (the roof fall rate is between 0.4 and 1.5 falls per 10,000 ft)
- *Successes* (the roof fall rate is less than 0.4 falls per 10,000 ft)

With the discriminant analyses separating *Failures* and *Successes* such that the *Intermediate* category essentially represented the design condition. Essentially ARBS represents a roof support design technique that hopes to reduce roof fall rates rather than eliminate them.

The above definition/categorisation of roof failure (or level of roof falls) would be totally unacceptable in the Australian underground coal industry. This discussion highlights that a country's tolerable level of risk is a critical factor in the level (and type of support e.g. bolt length) utilised and in developing a roof support design methodology; and also why the use of multiple linear regression, based solely on the satisfactory cases, was the appropriate approach for the development of a maingate belt road roof support design technique for Australian longwall operations.

With respect to cable length selection, it is strongly recommended that cable length should be determined such that it is suitably anchored in competent upper roof strata and that it exceeds the potential/likely HOS during longwall retreat. Prior colliery experience, the supplier's recommendations on anchorage length and the use of AMCMRR can assist in this assessment.

ROOF SUPPORT PATTERNS

Research has found and it has been explained on numerous occasions during workshops/training courses; if a pit has a reasonable understanding of its geotechnical environment including nature's variation within that environment and the ability to predict or at least account for such variations, in terms of the data inputs to ALTS 2009, ADFRS and ADRS, then the resultant data outputs will virtually always be consistent and correlate well with the required roof/rib support levels to maintain satisfactory roadway conditions.

The roof support (i.e. PRSUP and GRSUP) ranges provided in ALTS 2009 allow an engineer "to be an engineer" and make judgements. A suitably qualified geotechnical engineer with a reasonable level of underground coal experience and trained in the use of ALTS 2009 should be able to readily make these judgements, such as how to convert the selected/design PRSUP and GRSUP into a suitable balance of bolts and longer cables and where to position the tendons.

For example, if one were to employ a six bolt primary roof support pattern then the positioning and angle of installation of the two outer and two inner bolts is dictated to a large degree by the continuous miner, does one then need to be Einstein to work out where the 5th and 6th bolts should be installed?

Furthermore AMCMRR, which was developed to be utilised to complement ALTS, requires as data input the tendon position across the roadway, its angle of installation, length, pre-load applied and whether it is fully encapsulated, point anchored and/or post-grouted, such that ALTS 2009 and AMCMRR should be used in conjunction with one-another for the best design outcome.

In terms of where in the support ranges one selects as the design PRSUP and GRSUP; during the ALTS training courses numerous and simple commonsense examples are provided e.g. achieving poor encapsulation – move higher in the range, high level of confidence in CMRR selected – stay near the recommended, the pit considers they have the best and most conscientious development crews in Australia which is supported/confirmed by routine audits (e.g. pull tests) – possibly move lower in range, the continuous miners employed by the pit can't close up the cut-out distance from the face to last line of support sufficiently when encountering significant roof movement on development – move higher in the range, the colliery has in place real time extensometry monitoring as well as a properly considered TARP that is conscientiously adhered to – potentially move lower in the range and the list of issues to consider goes on.

The ALTS database intrinsically deals with all these issues and the design recommendations emanating from ALTS correlate with manageable levels of risk that have been assessed in terms of an Australian database and the geotechnical engineer using ALTS 2009 for maingate belt road roof support design can take great comfort in the fact that approximately 90% of the reason(s) for the level of roof support required is accounted for by reasonable estimates for the CMRR and the horizontal stress acting across the roof.

CONCLUSIONS

The idea portrayed by some that empirical modelling per se and the resultant statistical relationships are simplistic and are limited in their application is at best misguided and at worst, misleading. Quality empirical modelling i.e. empirical modelling based on a sound mechanistic understanding of the geotechnical environment; is in fact a scientific process of significant challenge and complexity.

With respect to the underground coal geotechnical environment; empirical modelling allows for the development of practical and fully engineered design methodologies and techniques/tools that can provide an entire industry and the minesite strata control engineer with timely solutions to complex geotechnical design issues. The development and success of ALTS 2009, ADRS and ADFRS for geotechnical design are also consistent with the thoughts of Hustrulid (2006) where he indicates that marked progress in the field of mining rock mechanics requires, “the careful collection, analysis and presentation of field/mine experience.”

In relation to empirical modelling Salamon (1989) states, “The main advantage of this approach is its firm links to actual experience. Thus, if it is judiciously applied, it can hardly result in a totally wrong answer. Also, in our legalistic world, it has the added advantage of defensibility in a court of law. After all, it is based on actual happenings and is not just a figment of imagination”. ALTS 2009, ADRS and ADFRS go even further, as the statistical relationships and the way they are utilised as a part of the design methodologies intrinsically represent a tolerable level of risk specific to Australian collieries, which a numerical modelling approach (as employed in the Australian underground coal industry) is simply not capable of doing.

While being a strong advocate for the advancement of numerical analysis, Salamon (1989) gave a reasonable and professionally balanced view when discussing both numerical and empirical techniques and was of the belief that mathematical modelling (not numerical as Galvin, 2016 indicates) is essential in the field of strata control. Of course getting the mathematical modelling/equations correct is crucial within many branches of science such as spaceflight trajectory/analysis. If the mathematics is wrong or necessary mathematical equations/code are missing, then the programmed computer model can be worthless or even dangerous leading to disastrous results.

As indicated in the introduction, it is the world of medicine and medical/pharmaceutical research and their approach in dealing with nature that has had a significant impact on the author’s approach to the natural environment associated with strata control. The interested reader is referred to the Australian Clinical Trials website (www.australianclinicaltrials.gov.au) where under “Your stories” there are many interesting stories from patients, researchers and medical practitioners concerning the benefits of clinical trials. However probably the most poignant statement is that of researcher Robyn Ward, then Professor of Medicine and Director of the Cancer Centre at Prince of Wales Hospital and University of New South Wales, “Knowing what works and what doesn’t is fundamental to the evidence base that underpins medicine. Without it, we are just snake oil salesmen.”

Professor Ward's statement of course applies to all branches of science and while not using the same colourful language similar sentiments are expressed by Hustrulid (2006) and Salamon (1989) with respect to the need for real world evidence and justification for the development and use of geotechnical design techniques.

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